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VLBI for *Gravity Probe B*. I. Overview

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ABSTRACT

We describe the NASA/Stanford gyroscope relativity mission, *Gravity Probe B* (*GP-B*), and provide an overview of the following series of six astrometric and astrophysical papers that report on our radio observations and analyses made in support of this mission. The main goal of this 8.5 year program of differential VLBI astrometry was to determine the proper motion of the guide star of the *GP-B* mission, the RS CVn binary IM Pegasi (IM Peg; HR 8703). This proper motion is determined with respect to compact, extragalactic reference sources. The results are: -20.833 ± 0.090 mas yr⁻¹ and -27.267 ± 0.095 mas yr⁻¹ for, respectively, the right ascension and declination, in local Cartesian coordinates, of IM Peg's proper motion, and 10.370 ± 0.074 mas (i.e., 96.43 ± 0.69 pc) for its parallax (and distance). Each quoted uncertainty is meant to represent an $\sim 70\%$ confidence interval that includes the estimated contribution from systematic error. These results are accurate enough not to discernibly degrade the *GP-B* estimates of its gyroscopes' relativistic precessions: the frame-dragging and geodetic effects.

Subject headings: astrometry — binaries: close — gravitation — radio continuum: stars — radio continuum: galaxies — relativity — stars: activity — stars: individual (IM Pegasi) — techniques: interferometric

1. Introduction

According to Einstein's theory of general relativity (GR), space-time is affected by both the Earth's mass and its angular momentum. The kinematics of bodies orbiting the Earth are thereby

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altered from their expected behavior based on Newton’s theory of gravity. In particular, according to GR, the spin axis of an ideal, freely-falling gyroscope near the Earth should exhibit two distinct non-Newtonian precessions due to these two properties of the Earth. These precessions can be considered as rotations of any near-Earth inertial frame with respect to the distant universe. The NASA/Stanford *Gravity Probe B* (*GP-B*) satellite was placed in low-Earth orbit on 2004 April 20 to measure these rotations.

The *GP-B* spacecraft provided a nearly freely-falling (“drag-free”), magnetically shielded, and thermally stable environment for its set of four close-to-identical gyroscopes (hereafter, “gyros”) of novel design and unprecedented stability and accuracy. The design and performance of these gyros are documented at length elsewhere (see, e.g., Conklin & the Gravity Probe B Collaboration 2008; Keiser & Gravity Probe B Collaboration 2009, and references therein). We describe here the key features of this experiment, emphasizing the dependencies on astronomical measurements.

The four gyros provided a fourfold redundancy to increase the reliability of the experimental results. Each gyro rotor consists of a 3.8 cm-diameter quartz sphere with about a 40-atom-thick niobium coating which is superconducting at temperatures below 1.8 K. The four gyros were separately electrostatically suspended within a structure largely made from a single block of quartz, which provided a rigid framework with respect to which the orientation of the spin axis of each gyro could be measured. In turn, the orientation of this structure with respect to the distant universe could be determined as a result of its rigid attachment to a guide telescope that was “locked” on a specific bright star, the “guide star,” when gyro measurements were being made. To maintain the rigidity of the telescope (and its attachment to the gyro housing), the telescope body, too, was made of solid quartz. The placement of this entire package within a large dewar containing, at launch, $\sim 2,400$ liters of superfluid helium allowed for ~ 17 months of continuous cryogenic operation of the gyros in orbit. To fit within a dewar, this telescope was not only limited in size to a 15 cm diameter aperture, but also reduced in light-gathering power by $\sim 25\%$ due to its required placement behind a stack of four vacuum windows built into the neck of the helium dewar.

To reduce errors resulting from nonrelativistic torques on the gyro rotors due to gravitational, electrical, and magnetic interactions between the rotors and the *GP-B* spacecraft, all four gyros were placed on the optical axis of the telescope and all four spin axes were aligned with that axis to within 10 milliarcseconds (mas). In this configuration, a high degree of reduction of the time-averaged nonrelativistic torques was achieved by slowly rolling the entire spacecraft about this common axis throughout the mission; the roll period was 77.5 seconds. To further reduce systematic errors, the spin-axis direction of the second and fourth gyros in this linear array was the same, but their spin vectors were oriented 180° opposed to those of the first and third gyros. The primary astronomically relevant consequences of this spacecraft design were that a single guide star had to be used for the entire *GP-B* experiment and that only a bright star could serve this function.

The orbit selected and subsequently achieved for the mission was also largely dictated by the

desire to separate the two relativistic effects from each other and to minimize the vector average over the mission of the nonrelativistic, gravitational torques on the gyro rotors. Numerical studies completed many years before launch led to the choice of a nearly circular, ~ 640 km altitude, polar orbit, with the orbital plane to be oriented so as to ensure that the line of sight to the eventually-selected guide star would lie, on average for the mission, within ~ 1.5 arcminutes of the orbital plane of the spacecraft (G. Keiser 2009, priv. comm.). A polar orbit ensured that the relativistic precession of the spin axes about the orbit pole, due to the orbital motion of the spacecraft (usually termed the “geodetic” precession), would lead to the gyro spin axes drifting in the north-south direction. (There is also a relatively very small geodetic contribution from the Sun, resulting in a drift in ecliptic longitude, which is taken into account in the analysis.) On the other hand, the predicted “frame-dragging effect,” due to the rotation of the Earth (often called the “Lense-Thirring” or “gravitomagnetic” effect), would lead to the gyro spin axes drifting eastward or westward, depending upon the instantaneous latitude of the gyros. The key required results from the *GP-B* spacecraft data analysis are therefore the north-south and east-west components of the orbit-averaged rates of precession of the gyros with respect to the apparent direction of the guide star. Similarly, the key required astronomical inputs to the relativity tests are the two components of the mean rate of the apparent angular motion of the guide star with respect to the distant universe. (Here and hereafter we use the word “mean” to denote an average for the time interval for which precession data were collected. Also, we use “apparent” to reflect the fact that effects such as aberration are not completely averaged out over the mission.) Of additional importance is the distance to the guide star, needed to make the annual parallax correction in the analysis of the *GP-B* data; our VLBI program provides this value with high accuracy (see below).

The time periods over which the gyros were monitored to collect precession data were confined to the interval from 2004 August 27 to 2005 August 15. The guide star was visible from the spacecraft for about half of each orbit. Generally, the attitude control system of the spacecraft could lock the orientation of the spacecraft to the direction of the guide star within ca. 2 minutes of its coming into view. Only data obtained when the spacecraft was locked on the guide star were used to estimate the relativistic precessions of the gyros.

When averaged over an integer number of contiguous complete orbits, each relativistic precession can be considered to occur at a uniform rate. For the orbit of *GP-B*, general relativity implies (see, e.g., Keiser & Gravity Probe B Collaboration 2009) that the average rate of geodetic precession is $\sim 6''.6 \text{ yr}^{-1}$, while that due to frame-dragging is $\sim 39 \text{ mas yr}^{-1}$. The nominal, pre-launch, accuracy goal of *GP-B* was a $\leq 0.5 \text{ mas yr}^{-1}$ standard error in each precession. At the time of launch, the mission error budget allowed for a 0.15 mas yr^{-1} contribution from astronomical phenomena to each of these two standard errors; by far the most important contributor to each was the allowance for the proper motion of the guide star. The two largest contributors to the overall error budget in this pre-launch analysis were the residual nonrelativistic torques on the gyros and the noise in the readout of the gyros; for discussion, see Keiser & Gravity Probe B Collaboration (2009).

The above description of the *GP-B* mission implies that several astronomical considerations and measurements were crucial to its success. A very distant extragalactic object would provide a nearly ideal tie to the distant universe. But all such objects are far too dim to be used directly. A bright intermediary was therefore required: the guide star. A prime consideration was the selection of that star. The obvious requirements were that it be sufficiently bright and isolated on the sky, and also suitably located to nearly maximize the sensitivity of the frame-dragging test. Another critical requirement for the guide star was that its proper motion either already be known at the required accuracy or be measurable to that accuracy. In 1989, when *GP-B* seemed poised to enter mission status, it was clear, as it had been previously, that there was no bright star whose proper motion was known to even close to 0.15 mas yr^{-1} . The *Hipparcos* astrometry spacecraft (Perryman et al. 1992; Perryman & Heger 1993), launched in that year, was not expected to achieve such accuracy. On the other hand, many years earlier very-long-baseline interferometry (VLBI) at centimeter wavelengths had yielded submilliarcsecond relative position accuracy for compact extragalactic radio sources nearby to one another on the sky (see, e.g., Shapiro et al. 1979; Marcaide & Shapiro 1983; Bartel et al. 1986), and hence was capable of yielding the desired accuracy in the proper motion of a guide star that was visible at radio wavelengths (I.S., ca. 1975, priv. comm. to C. W. F. Everitt). Moreover, by 1990 submilliarcsecond accuracy had also been obtained for a faint radio emitting star with respect to an extragalactic radio source $\sim 1^\circ$ away on the sky (Lestrade et al. 1990). Therefore, the *GP-B* project gave increasing attention to the ultimately adopted option of using VLBI to determine the proper motion of an optically bright radio star. A combination of spacecraft engineering requirements and the results of our program of radio observations of various guide-star candidates led to the selection in 1997 of IM Pegasi (IM Peg; HR 8703) as the guide star. We describe the investigations that led to the selection of this chromospherically active binary star in § 2 of this paper.

Once IM Peg had been selected, the bulk of the astronomical effort went into the determination of its proper motion via a sustained VLBI observation program, primarily at 8.4 GHz ($\lambda \simeq 3.6 \text{ cm}$). We also utilized earlier VLBI observations of IM Peg at this same radio frequency made from 1991-94 by Lestrade et al. (1999). In addition, at our behest, many groups made observations of different kinds at frequencies from ultraviolet to radio. The major motivation for these latter observations was the need to measure or bound any difference between the proper motion of IM Peg as determined with the VLBI technique and the proper motion of IM Peg as it would be observed by the *GP-B* spacecraft in the wavelength range 0.3 to 1.1 nm. Although this difference was never expected to be so large as to degrade the accuracy of the mission, several possible contributions to this difference had to be investigated observationally to meet the mission requirement for an exceptionally high level of confidence in its tests of general relativity. These contributions are highly dependent on the properties of IM Peg, which we discuss in § 3 of this paper.

There were two other ways in which the *GP-B* experimenters made use of astronomical knowledge. First, because the *GP-B* spacecraft continually rotated with a period of 77.5 s about the line of sight to the guide star (to within $0''.2$ rms when locked; Keiser & Gravity Probe B Collaboration

2009), determination of the north-south and the east-west components of the relativistic precession of the gyros required knowledge of the roll phase of the spacecraft. This roll phase was needed to transform both the gyro orientation measurements and the guide-telescope-pointing measurements from the frame of the rotating spacecraft to a quasi-inertial frame. The roll phase was modeled based upon the outputs of the CCD detectors of two small star-tracking telescopes that were fixed to the outside of the spacecraft, aimed at angles of 50° and 60° to the optical axis of the main guide telescope. With each roll of the spacecraft, each star tracker viewed an 8° wide band of the sky. The inference of spacecraft roll phase from the CCD readouts required adequate knowledge of the astrometric positions of the brighter stars in these bands. In fact, the $\sim 1''$ accuracy requirement on these positions was easily satisfied by existing astronomical catalogs and required no new observations.

Second, the aberration of the light from the guide star had to be determined to compute the orientation of the spacecraft from the *GP-B* telescope readout data. Thus the constantly changing spacecraft velocity with respect to the solar-system barycenter (SSB) had to be computed. Spacecraft tracking data, as well as data from an on-board GPS receiver, were used to determine the spacecraft velocity with respect to the center of the Earth; the velocity of the Earth with respect to the SSB was calculated from planetary and lunar ephemerides. Similarly, the relative positions of the Earth, Sun, and planets were needed to compute the guide star’s apparent motion due to parallax and the deflection of the star’s light by the Sun’s mass. Existing ephemerides exceeded by several orders of magnitude the accuracies of velocities and positions needed for the *GP-B* mission. The Galactocentric acceleration of the SSB can be neglected (Sovers et al. 1998), and presumably also the effect of a putative Nemesis solar companion or some as yet unknown nearby dark cloud (see also Paper III of this series, Bartel et al. 2011). These latter possibilities will either be confirmed or bounded at a useful level after, e.g., the Large Synoptic Survey Telescope goes into operation.

Another critically important application for the *GP-B* mission of the very accurately known values of the amplitudes, periods, and phases of the aberration components of IM Peg is their use as essentially error-free calibrators for the conversion of the SQUID readouts of the gyros from electrical to angular units (Keiser & Gravity Probe B Collaboration 2009). All in all, the design of the *GP-B* spacecraft assured that the astronomical effects on its relativity mission could not only be adequately determined, but also could be used to advantage in the analysis of the spacecraft data.

This paper is the first of a series of seven describing the astronomical effort we undertook to support the *GP-B* mission. In the preceding paragraphs we indicated the range of astronomical information required by the mission. Below we specify the requirements quantitatively, and outline how they were met. We then describe the six following papers in this series. In addition, we document certain aspects of the program that can be logically and adequately covered here.

In § 2, we describe the history behind the selection of IM Peg as the guide star, including the scope and results of an ~ 60 hr VLA search for radio emission from ~ 1200 bright stars. We then

summarize in § 3 the stellar and orbital properties of the IM Peg binary, and comment on some significant characteristics of its location in the sky, based on extensive observations primarily at optical wavelengths. Section 4 contains descriptions of the compact, extragalactic radio sources used to determine the guide star’s proper motion with respect to the distant universe; § 5 mainly describes our procedures for making VLBI observations of these sources. In § 6, we summarize the six specialized papers of this series. Section 7 treats our initial, but now dashed, hopes for a “double-blind” experiment, and § 8 lists our main conclusions.

2. Selection of IM PEG as the Guide Star

An obvious requirement for the guide star was that it be sufficiently bright. As the spacecraft design evolved, this requirement became much less stringent than had been envisioned earlier. For many years, the design called for photomultiplier tubes to be used as the light detectors of the star-tracking system. Not until the mid 1990’s was it considered safe to assume that the final design would, instead, use photodiode detectors, which had higher quantum efficiency, peaking at $\sim 80\%$ between 0.5 nm and 1.0 nm. They also generated so little heat that they could be placed inside the helium dewar without boiling off helium at a rate that would significantly shorten the cryogenic lifetime of the spacecraft, in fact $< 1\%$ (J. Turneure 2009, priv. comm.). This internal placement, behind each of the two focal planes of the telescope removed the need for light pipes to transmit the starlight out of the dewar, and hence reduced the transmission losses in the system. Based upon consideration of the resulting photon noise, B. Lange (1994, priv. comm.) estimated that a guide star could be marginally bright enough even at $V = 10.7$ for stars of spectral type G or K. However, the expected levels of noise in the amplifiers used to generate the telescope read-out signals implied that the maximum truly acceptable guide star V magnitude was ~ 7 (J. Kasdin 1994, priv. comm.). Both of these limits were set with the intention that the uncertainty of the measured pointing of the spacecraft averaged over operationally relevant intervals would not unacceptably degrade the real-time attitude control of the spacecraft. The minimum brightness required to avoid having telescope read-out noise degrade the final estimates of the relativistic precessions of the gyros was less stringent, and so automatically satisfied (Keiser & Gravity Probe B Collaboration 2009).

For most of the period of development of the *GP-B* mission, the nominal guide star was the very bright Rigel ($V = 0.1$). In 1989, when we began to intensively investigate the possibility of replacing Rigel with a radio star observable with VLBI, one of our first tasks was to investigate what the optically brightest suitable radio star might be. Before describing our efforts and conclusions concerning that question, we first specify what additional factors went into evaluating the suitability of guide-star candidates.

First and foremost, a low declination for the guide star maximized the sensitivity of the mission to the frame-dragging effect, since the magnitude of that effect on the motion of the gyro spin axes on the sky was proportional to the cosine of the spin-axis declination, which had to be very nearly the same as that of the chosen guide star. Since the errors in the measurements of gyro drift rates

were not expected to depend sensitively on declination, the fractional accuracy with which the frame-dragging effect could be measured would be maximized by a declination value of 0° . On the other hand, if the expected error in the VLBI determination of the proper motion of a given guide-star candidate were significantly smaller than that for another candidate nearer to 0° declination, the former candidate might nevertheless have been a better choice than the latter. However, as was correctly anticipated, if the gyro drift-rate measurements were considerably less accurate than the proper motions determined by VLBI, then any compromise on the declination criterion could significantly decrease the fractional accuracy of the frame-dragging test. Nevertheless, out of concern that we might find no fully suitable radio star with the preferred low declination, we examined stars with declinations as high as $+60^\circ$ and as low as -30° . We considered any star yet further south to be too difficult a target for accurate VLBI astrometry, since the antennas available to us were predominantly located in the northern hemisphere.

Working against the declination preference was a strong preference for a guide star more than $\sim 20^\circ$ from the ecliptic. For guide stars at this or a greater angular distance from the ecliptic, a sun shield could be placed around and in front of the telescope windows to largely prevent sunlight from entering the dewar and boiling off the helium even at the time of year when the sun was closest to the direction of the guide star. The scattering of direct sunlight by the windows was also a potential source of error for the star tracker. In case this ecliptic-separation criterion was later relaxed, we included in our guide-star search candidate stars that were as little as 10° from the ecliptic.

In 1996, as the time for selection of the guide star approached, it became clear that stars much higher in absolute ecliptic latitude than 30° were unacceptable. Because the spacecraft was to continuously rotate about the line of sight to the guide star, while its solar panels had to remain fixed on the spacecraft, the roll-averaged amount of electrical power from them varied with the ecliptic latitude and the time of year. During the early and mid 1990's both the power requirements of the spacecraft and the expected power output of the solar panels evolved. Only in 1997 did the project team conclude that, for the range of then practical spacecraft designs, adequate power could not be guaranteed for stars as far as $\sim 40^\circ$ from the ecliptic. As discussed below, this problem directly impacted the final choice for the guide star.

The design of the guide-star telescope made it sensitive to light from all astronomical sources within $\sim 80''$ of the guide star: With the spacecraft locked on the guide star to within a few arcseconds, light from this surrounding field of view would fall on the detectors. Moreover, the smaller the ratio between the guide-star brightness and that of background stars, the stricter the requirement became for accurate knowledge of the time dependence during the mission of that brightness ratio. This restriction, too, as we'll see below, resulted in the elimination of an otherwise promising guide-star candidate.

The most fundamental requirement on the guide star is that its proper motion be known, or known to be measurable, with sufficient accuracy in an adequately inertial reference frame. What

was this accuracy requirement? Given that the *GP-B* team wished to perform the two relativity tests as accurately and convincingly as feasible, and given that the tests each required an additive correction for the proper motion, any specific requirement needed to be justified in terms of the relative costs and benefits of reducing the uncertainty contributed by each source of experimental error. Only in 2003, the final year before launch, did the project approve a formal requirement. It called for the standard error in the estimate of the proper motion of the guide star over the course of the mission to be no more than 0.14 mas yr^{-1} in each coordinate. This somewhat odd value was specified so that the total uncertainty due to all astronomical phenomena would have a standard error no more than 0.15 mas yr^{-1} after allowance was made for an additional standard error of 0.05 mas yr^{-1} for the independent effect of any background light in the guide-star telescope’s field of view.

The 0.15 mas yr^{-1} requirement was chosen in light of highly uncertain estimates of the non-astronomical experimental errors. The nominal goal of the mission design was to measure each relativistic effect with a total standard error $\leq 0.5 \text{ mas yr}^{-1}$. However, there was at that time no identifiable reason why, in the event of a flawless mission, the *GP-B* gyro measurements could not collectively yield a full order of magnitude higher accuracy. At the time (2003) that the proper-motion requirement was formalized, we could predict with good reliability that the series of VLBI observations we began in 1997, if continued through the end of the *GP-B* flight mission, could meet the 0.14 mas yr^{-1} requirement, even with the analysis allowing for the possibility of a long-term proper acceleration due to an as yet unknown, bound companion to the chosen guide star in an orbit with period of several decades or more (see § 3, below, concerning shorter periods). Higher accuracy in the proper-motion determination could be obtained by continuing the VLBI measurements as long into the future as required.

The above discussion of the constraints on the guide star is summarized in Table 1. These constraints, however, are not rigid, and the choices for guide star were quite limited, as we discuss in the following paragraphs.

Table 1. Constraints on Choice of Guide Star

Characteristic	Approximate constraint
Brightness (mag)	$V \lesssim 7$
Declination (deg)	$-20 \lesssim \delta \lesssim +20$
Distance, D , from ecliptic (deg)	$20 \lesssim D \lesssim 40$
Minimum magnitude difference between guide star and any background star within $4'' - 40''$ (with gradual relaxation outside this range) (mag)	10
Standard error in final estimate of each component of guide-star proper motion (mas yr^{-1})	≤ 0.14

Ground-based optical astrometry could not provide proper motions with the required accuracy. For example, in the Fifth Fundamental Catalogue (FK5, Fricke et al. 1988), the mean individual error of proper motion in right ascension for stars with $\delta > -30^\circ$ is $\sim 6 \text{ mas yr}^{-1}$. The *Hipparcos* satellite, launched in 1989, unfortunately into the wrong orbit (Perryman & Heger 1993), didn't seem destined to be able to meet the *GP-B* requirements. Even after the miraculous completion of the *Hipparcos* program, resulting from clever “workarounds,” the published catalog (ESA 1997) shows that virtually all nominal standard errors of the proper motions are greater than 0.5 mas yr^{-1} in each coordinate. Moreover, in spite of a large, multi-pronged effort to tie the reference system of the *Hipparcos* Catalogue to a VLBI-governed International Celestial Reference Frame, the uncertainty of the rate components of that frame tie was at least 0.25 mas yr^{-1} (Kovalevsky et al. 1997), which was also expected to be unacceptable for *GP-B*. In addition, since the median epoch of the *Hipparcos* observations was 1991.25, a proper acceleration of the guide star, due to an undetected bound stellar companion in a long-period orbit, plausibly could have caused the apparent proper motion of that star during the year of the *GP-B* mission to be subject to an offset larger than the nominal standard error of the star's estimated proper motion at epoch 1991.25. Worse is the later Tycho-2 Catalogue (Høg et al. 2000), based on the combination of *Hipparcos*/Tycho positions (but not the associated proper motions) and all usable ground-based positions (spanning about a century). These provide proper motions with an estimated standard error of 2.5 mas yr^{-1} in each coordinate. Finally, although modern optical methods can achieve differential positional accuracy over single instrumental fields of view on the order of 1 mas in a single night, it has not yet been demonstrated that a decade or so of such observations can yield proper-motion standard errors even as low as 0.2 mas yr^{-1} .

In contrast to the apparently inadequate accuracy of these optically determined proper motions, the accuracy of the upper bounds on the proper motion of compact, extragalactic radio sources derived from VLBI observations well exceeds the requirements of *GP-B*.

How do all of these considerations combine to affect the choice of the guide star? From our VLA survey (1990-1992) and among previously known radio stars, we found only four potentially satisfactory guide stars: λ Andromeda (HR 8961, $+46^\circ$ declination), HR 1099 ($+1^\circ$), HR 5110 ($+37^\circ$), and IM Peg (HR 8703, $+17^\circ$). All were known to be RS Canum Venaticorum-type radio emitters before we conducted our radio survey at 8.4 GHz of about 1200 other stars with V magnitude of 6.0 or brighter. Thus our survey yielded no detections of previously undetected stellar radio emission. Our results were confirmed by a substantially deeper, more comprehensive, later survey by Helfand et al. (1999), which disclosed no further stars suitable to be *GP-B* guide stars; all failed on either or both of brightness and declination grounds. Following up on the four candidate guide stars, we examined the fields around each and checked as well on possible reference sources: compact extragalactic radio sources nearby on the sky to each candidate. The *GP-B* project, in consultation with us, concluded that IM Peg was the best choice; the corresponding frame-dragging of the spacecraft was predicted to be $\sim 40 \text{ mas yr}^{-1}$; HR 5110 was a reasonably close second. Its elimination was based mainly on its high ecliptic latitude of $+43^\circ$.

HR 1099 was rejected as the GP-B project was unsure whether, in the data analysis, the variation in the ratio of the brightness of HR 1099 ($V \sim 5.7$) to that of a $V \sim 8.8$ star that would also be in the telescope’s field of view could be measured to the accuracy needed to avoid possibly degrading the accuracy of the relativity measurements. In addition, each time the telescope initiated its lock on the guide star, there would have been a risk of locking on the wrong star, at least temporarily. The last remaining alternative to IM Peg, λ Andromedae, was dropped because of its high declination and weak and variable (typically 0.4 to ~ 1 mJy) radio emission.

3. Properties of IM Peg and its Surroundings

IM Peg is a known binary star with a variable magnitude; see Table 2 for the observed maxima and minima of its V magnitudes during the *GP-B* mission. The sky position of IM Peg as well as its orbital elements are also shown in this table. For IM Peg, no other star within $12'$ is brighter than V magnitude 10, compared with a corresponding average brightness of IM Peg of about 6.

We made quite extensive, but unpublished, investigations into possible systematic errors of the *GP-B* measurements due to both known and unknown, but plausible, optical properties of IM Peg and the field of view of the *GP-B* guide telescope when it was locked on IM Peg. We were particularly concerned that the photospheric spots (analogous to sun spots, but much larger) that characterize the primary component of RS CVn binaries like IM Peg, could cause the apparent center of the guide-star telescope image of IM Peg to systematically drift with respect to our VLBI-derived proper motion of the center of mass of the system. A program of spot mapping by S. Marsden and S. Berdyugina of ETH-Zurich (Marsden et al. 2007), using optical spectroscopic observations, found no such effect, and ruled out errors larger than 0.04 mas yr^{-1} . Among the spectroscopic observations used to reach this conclusion were two full observing seasons of near nightly observations, effectively covering the entire *GP-B* mission. These data were obtained by J. Eaton of Tennessee State University with the TSU Automated Spectroscopic Telescope (Fairborn Obs., Paradise Valley, AZ).

A second class of conceivable errors encompassed all those that could arise due to the photometric variability of IM Peg in combination with sensitivity of the *GP-B* telescope to “background” light in its field of view; such latter effects could arise from point sources and nebosity, whether constant or variable. These possibilities, too, were ruled out, on the basis of a wide variety of observations obtained in support of *GP-B*. Notable among these observations were images obtained by us as we searched for unknown stellar companions (or nebosity) with the WFPC2 instrument on HST (using filters ranging from IR to UV), by P. Kalas (UC Berkeley) with his “coronagraphic” camera on the U. Hawaii 2.2 m telescope (Mauna Kea), by L. Roberts (then at Boeing) with the Advanced Electro-Optical System Telescope (USAF Res. Lab., Haleakala), by E. Horch (U. Mass. Dartmouth) via speckle interferometric observations using WIYN (Kitt Peak), and by X. Pan (Caltech) with the Palomar Testbed Interferometer. T. Dame (CfA) used the CfA’s 1.2 m aperture radio telescope to map the sky near IM Peg in CO(1–0) millimetric emission to rule out any com-

Table 2. Optical properties of IM Peg

Property	Value	
<i>Hipparcos</i> ^a 1991.25 RA (J2000)	22 ^h 53 ^m 02 ^s 278706 ± 0.63 mas	
<i>Hipparcos</i> ^a 1991.25 DEC (J2000)	16° 50′ 28″53982 ± 0.43 mas	
Approximate galactic longitude, l^{II}	86.4°	
Approximate galactic latitude, b^{II}	−37.5°	
<i>Hipparcos</i> Parallax ^a (mas)	10.33 ± 0.76	
<i>Hipparcos</i> Distance (pc)	96.8 ± 7.1	
Spectral type of primary ^b	K2 III	
V magnitude range: ^c	5.7 to 6.0	
Spectroscopic orbital elements: ^d		
Period, P (days)	24.64877 ± 0.00003	
Eccentricity, e	0.0	
Superior conjunction of primary, ^e T_{conj}	2,450,342.905 ± 0.004	
Mass ratio, M_2/M_1	0.550 ± 0.001	
Velocity amplitude, K (km s ^{−1})	34.29 ± 0.04	62.31 ± 0.06
$a \sin i$ (R _⊙)	16.70 ± 0.02	30.34 ± 0.03
Mass function, $f(m)$ (M _⊙)	0.1030 ± 0.0004	0.618 ± 0.0002
$M \sin^3 i$ (M _⊙)	1.486 ± 0.007	0.818 ± 0.005
Orbital inclination, ^f i	65° ≤ i ≤ 80°	

^aESA (1997). The position is given for the catalog epoch, 1991.25.

^bBerdyugina et al. (1999) and Marsden et al. (2005).

^cNear daily photometry, save for ∼2.5 months when the Sun prevented observations, was obtained by G. Henry (2005, priv. comm.) during the mission.

^dMarsden et al. (2005). The values for the two binary components are given in two columns.

^eJulian date for heliocentric observations. Note: Superior conjunction refers to a body’s being furthest from us in its orbit.

^fBerdyugina et al. (1999). See also Lebach et al. (1999), who find $i \gtrsim 55^\circ$.

compact molecular cloud near IM Peg that might be associated with an optical reflection nebula. Based on these observations and a Bayesian probabilistic analysis by J. Chandler (CfA) and one of us (MIR), any astrometric errors due to undetected companions of IM Peg were bounded below 0.006 mas/yr with about 95% confidence, under plausible but conservative assumptions about the a priori distribution of third-body companions with respect to optical brightness, orbital parameters, and other characteristics. In addition, extensive optical photometry of IM Peg by G. Henry (TSU) using mainly the TSU Automatic Photometric Telescope (Fairborn Obs., Paradise Valley, AZ), and of the known background stars in the guide-telescope field of view by G. Gatewood (U. Pittsburgh), using the Allegheny Obs. Thaw telescope (Pittsburgh), and by A. Henden (then USNO), using the 1.55 m USNO telescope (Flagstaff), bounded any photometric variation of those stars during the *GP-B* mission sufficiently to rule out any significant resulting error in the *GP-B* measurements. All together, the above errors do not contribute as much as the 0.05 mas yr^{-1} standard error allowed for them in the *GP-B* error budget.

4. Radio Reference Sources for IM Peg

Our main goal is to determine the proper motion of IM Peg with respect to the distant universe. To this end, we sought compact, extragalactic radio sources which were effectively fixed markers in the distant universe. By using phase-referenced VLBI, we could determine the difference with time between the positions of IM Peg and those of the chosen extragalactic radio sources. What compact extragalactic radio sources did we choose? The main reference source we chose, 3C 454.3, is located on the sky 0.7° away from IM Peg. This reference source has a complicated, changing radio brightness distribution. Nonetheless, we made this choice, also motivated by 3C 454.3 having been used as the reference source for the VLBI observations of IM Peg in 1991-1994 (Lestrade et al. 1999). We wanted to thereby take advantage of the extended time span that would then be available for our determination of proper motion (see Paper V, Ratner et al. 2011, for discussion of the value of the earlier observations). To check on possible systematic errors that might affect the VLBI determinations of the sky position of IM Peg with respect to 3C 454.3, we added two more reference sources. One of these sources, the quasar B2250+194 (ICRF J225307.3+194234) was included ab initio, and was also used to distinguish between model errors that have elevation-angle dependence and those that do not. The other, B2252+172 (87GB 225231.0+171747), was added in 2002; although quite close to IM Peg and virtually a point source, it is a weak radio emitter and not always reliably detected. These latter two sources are far more compact than 3C 454.3, but are further away on the sky from IM Peg or very weak, as noted. The former is 2.2° away and the latter 0.9° away; see Figure 1 for the relative sky positions of all four sources. The redshift of 3C 454.3 is 0.859, whereas that of B2250+194 is 0.28. The third reference source does not have a known redshift, but its compact structure, flat microwave power spectrum (see Paper II, Ransom et al. 2011a), and lack of any detectable proper motion (see below) constitute in sum virtual proof of its extragalactic nature.

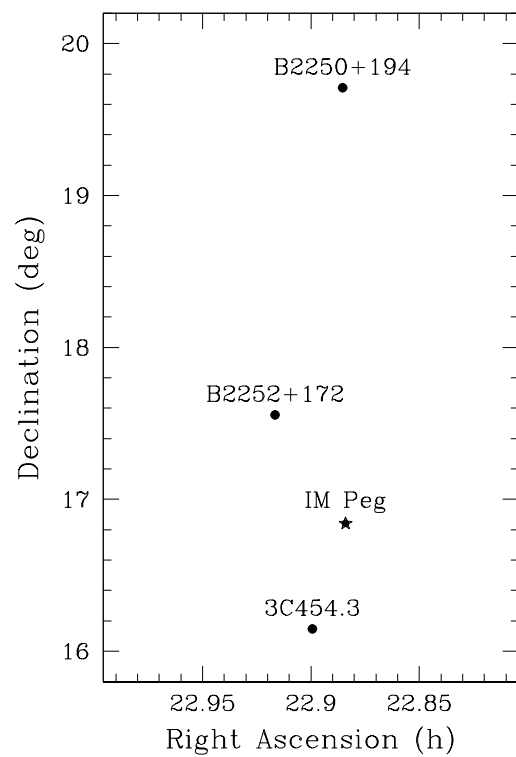


Fig. 1.— Positions (J2000) on the sky of the four radio sources used for *GP-B* astrometry. The east-west and north-south directions on the plot are shown to the same scale.

5. VLBI Observations for *GP-B*

The VLBI data that we gathered in each of our 35 observing sessions between 1997 and 2005 were obtained at 8.4-GHz, with the addition of 5 and 15 GHz data for one observing session (see Paper II). In each session, we used up to 16 antennas distributed globally. Our choice of 8.4 GHz as the primary observing frequency was based on its yielding the best combination of high sensitivity and high angular resolution when our full array of antennas was used. For each such session, observations were made in a repeating cycle that included the guide star and each reference source. This cycle extended over 5.5 minutes or somewhat ($<20\%$) longer for the earlier sessions and consisted of interleaved cycles of duration 5.5 and 7 minutes for the last 12 sessions, when the third reference source was included. (The latter pattern was a compromise we adopted to more nearly preserve the SNRs for our first two reference sources.) The cyclic pattern of observing was designed to reduce the effects on our results of systematic errors due to our inability to adequately model the temporal behavior at each antenna site of the clocks and the propagation medium, the latter consisting most importantly of the Earth’s atmosphere and ionosphere. (Had multiple antenna beams been available at each site, simultaneous observations could have been made of all of the target sources, obviating the need for the cyclic observing.) The downside of this mode is the difficulty in properly connecting the observed fringe phase from each cycle to the next so as to eliminate multiple 2π ambiguities (see below). Based on signal-to-noise-ratio considerations, we also chose to not observe simultaneously in two radio bands, even though such dual-band observations would have allowed us to largely free our VLBI data from ionospheric effects.

6. Synopsis of Series of Papers

This section is devoted to a synopsis of each of the remaining papers of this series.

Paper II focuses on mapping and analyzing the changing radio-brightness structures of the three compact extragalactic reference sources used in our determinations of the proper motion of IM Peg, the *GP-B* guide star. Paper II also describes our VLBI observations in detail, the reference sources used for each session, the processing needed to produce maps of the brightness distributions of those sources and of the guide star, and the resultant reference-source maps themselves (the maps of IM Peg are given in Paper VII; see below). Figure 2 shows a typical example of an 8.4 GHz image of the guide star and of each reference source. A summary of all of these observations—epochs, wavelengths, antennas, and sources—is presented in Paper II. Through the analysis of the radio images from our 35 sessions (spread over 8.5 years) of VLBI observations of 3C 454.3, our principal reference source, this paper establishes that a specific brightness component, dubbed C1, at the eastern end of the source, likely corresponds to the gravitational center of the source (the “core”) and to a putative supermassive black hole located there (see Figure 2). Small, under 0.2 mas, excursions of the brightness peak of C1 from this core location were tracked from session to session. These motions are plausibly attributed to the effects of occasional outbursts from the core which

manifest themselves as jets, initially unresolved, that move the peak of C1 westward. Then, as the jet separates further, the location of the peak becomes less affected and hence moves eastward back towards its “normal” position collocated with the core. This interpretation of C1 is bolstered by C1’s steep spectrum and by comparison of our 8.4 GHz images with contemporaneous and near contemporaneous images at 43 and 86 GHz frequencies. In addition, Paper II shows maps and presents analyses of the temporal evolution of the other compact components in the structure of 3C 454.3. The paper also establishes the utility of our two other reference sources as relatively structureless, nearly unchanging secondary reference sources for our VLBI astrometry of IM Peg.

Paper III (Bartel et al. 2011) delves deeply into the structure and behavior of the radio brightness of our main reference source, 3C 454.3. The primary goal of this examination for *GP-B* was to determine a stable feature in its radio brightness distribution, one which remained at a fixed location with respect to the center of mass of the source. This study led to our choice of C1 (see Figure 2) as the reference position in this source. From our full set of maps of 3C 454.3, one for each observing session, we were able to follow the evolution of this source’s radio brightness at 8.4 GHz with reasonably good time resolution over nearly a decade. A main thrust of Paper III is to establish, to a degree of reliability sufficient for the *GP-B* mission, that the C1 component of 3C 454.3 is stationary with respect to the distant universe, approximated by positions of extragalactic reference sources. We established this stationarity in Paper III, primarily by i) using our VLBI phase-delay observations to determine the position of C1 with respect to the positions of our other two radio reference sources, and then ii) determining the position of one of the latter (B2250+194) with respect to those of a large suite of compact extragalactic radio sources. To this latter end, we made use of the extensive ~ 30 years’ accumulation of astrometric/geodetic group-delay VLBI observations of 3C 454.3 (see Petrov et al. 2009, and references therein) that determine its position in a catalog formed from such observations of ~ 4000 of these sources that were observed rather regularly over this period.

Paper III concludes that $\sim 70\%$ confidence upper limits on the proper motion of C1 on the plane of the sky for the time period from 1998 to 2005 are $0.046 \text{ mas yr}^{-1}$ in the right-ascension and $0.056 \text{ mas yr}^{-1}$ in the declination directions. These limits notwithstanding, Paper III also presents evidence for C1 having a “jittery” east-west motion, with amplitude $\sim 0.2 \text{ mas}$, likely related to jet activity in the vicinity of the core, as discussed above for Paper II. Paper III also analyzes in detail the proper motions of the other radio-bright components of 3C 454.3, some superluminal.

In Paper IV we describe the novel data-reduction technique we used for *GP-B* in our effort to achieve as high an astrometric accuracy from our VLBI data as feasible. Our technique combines the superior model-correction capabilities of parametric model fits to VLBI data with the ability of phase-referenced maps to yield astrometric measurements of sources that are too weak to be used in parametric model fits. More specifically, we use VLBI data from our radio-bright reference sources in parametric model fits to improve our a priori models (in particular for propagation delays through the Earth’s atmosphere), and then use these improved models to make phase-referenced maps of our target sources. As shown in Paper IV, this technique has benefits for both

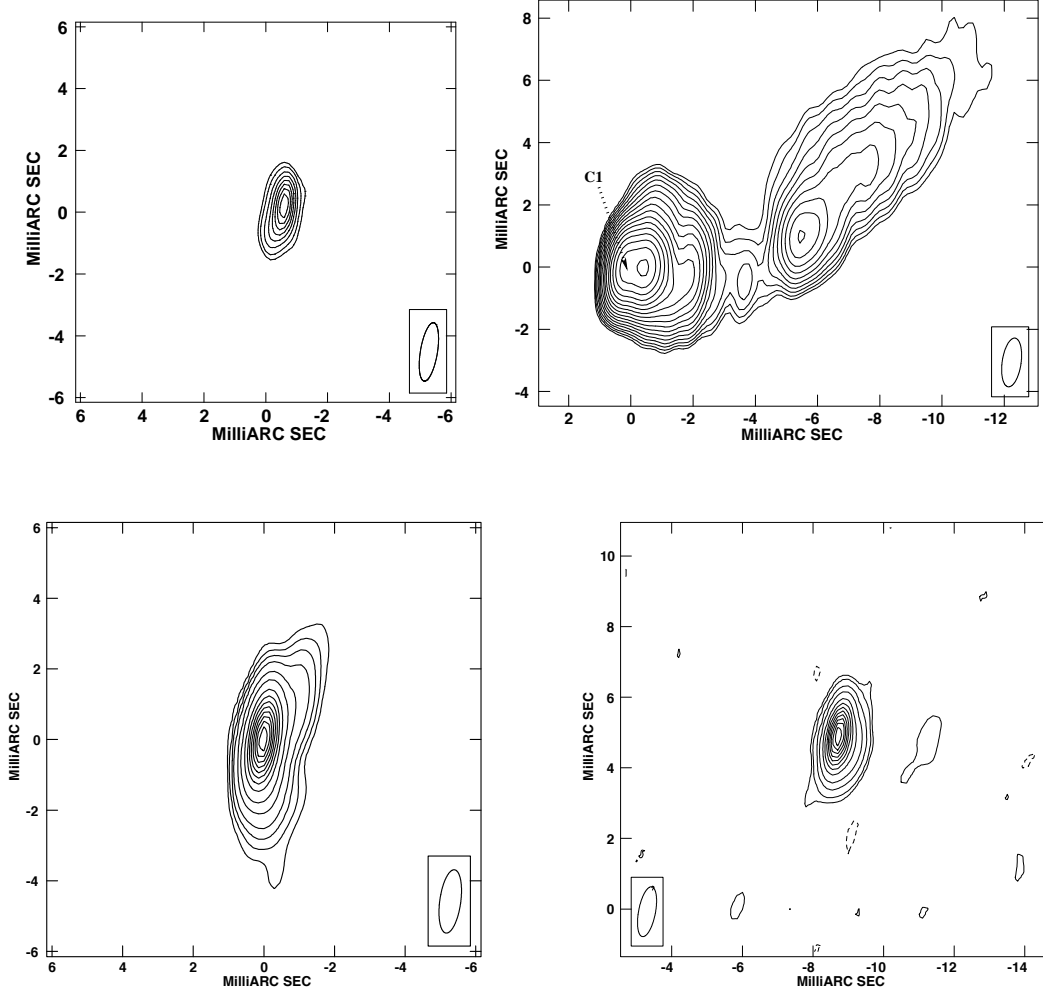


Fig. 2.— Sample CLEANed VLBI images at 8.4 GHz of IM Peg and our three VLBI reference sources, all at approximately the same scale. North is up and east to the left. The positions of the origins are not significant here. The upper left panel shows one of our higher SNR images of IM Peg, derived from all usable data from our 2004 December 11 observing session. As at most of our observing epochs, the detectable stellar radio emission consists of a single slightly extended component with little or no visible structure. The upper right panel shows 3C 454.3 at the same epoch. A well resolved core-jet structure is seen in all of our 3C 454.3 images. The component labeled C1, which we found to have no significant astrometric motion with respect to the peaks of our two other extragalactic sources, serves as our astrometric fiducial point (see text). The lower left panel shows B2250+194 on 2000 November 05. Extensions to the northwest and south are evident. The last panel (lower right) shows B2252+172, our most compact reference source, on 2003 May 8. In each panel the restoring beam used in processing the image is shown in the inset. These images are presented in the relevant papers of our series; see these for contour details.

our astrometry and the dynamic range of our target-source maps. Our technique also allowed astrometric results with submilliarcsecond accuracy to be obtained from each of our 35 sessions of VLBI observations of IM Peg, an outcome that may not have been possible with conventional techniques that use parametric model fits or phase-referenced maps alone. Paper IV also describes our successful strategy for removing 2π ambiguities from the fringe-phase data from the observations of our reference sources, a key element of our data-reduction technique.

Paper V in the series (Ratner et al. 2011) contains our astrometric analysis of the time series of positions for the radio source associated with IM Peg, determined as described in Paper IV. Using a weighted-least-squares algorithm, we determined the parameters, their uncertainties, and their correlations, for a model (and several variants) of the motion of this radio source. Each of these models has parameters representing sky position at a reference epoch, parallax, proper motion, and the orbit of the close binary system. The orbit is assumed circular with a known period, based on optical spectroscopic observations (see, e.g., Marsden et al. 2005); we also found consistency between our data and a zero eccentricity orbit, as well as with the optically-derived orbital period, which is determined far more accurately from the far longer series of optical spectroscopic data. The main alternative model considers the possible presence of a distant third body in the guide star’s system. This presence would lead, over the short term, to a proper acceleration as well as a contribution to the proper motion of the IM Peg binary. However, the estimates of the associated parameters yield values insignificantly different from zero. Our final result for IM Peg’s proper motion and parallax (see Table 3) is thus based on a 9-parameter model: 4 orbital parameters, 2 for sky position (right ascension and declination of the center of mass of the IM Peg binary at epoch), 2 components of its proper motion, and 1 parallax parameter (see Table 3 of Paper V).

Paper VI (Ransom et al. 2011b) examines the orbit of the radio emission of IM Peg, as projected on the sky, and compares the common properties with those deduced from optical spectroscopy. From the projected orbit and the different radio images—with one, two, or three components—obtained at different epochs, Ransom et al. develop a simple model of the radio

Table 3. IM Peg parameter estimates

Parameter	Estimate	Total SE ^a
μ_α (mas yr ^{−1}) ^b	−20.833	0.090
μ_δ (mas yr ^{−1})	−27.267	0.095
Parallax (mas)	10.370	0.074
Distance (pc)	96.43	0.69

^aEach “Total SE” entry is our estimate of the parameter’s standard error, inclusive of both statistical and estimated systematic errors, as described in Paper V.

^bThe notation here denotes the α component of proper motion multiplied by $\cos \delta$, i.e., the local Cartesian coordinate in the right-ascension direction.

emission. Simulations based on this model point to the brightness peaks of the radio emission at the various epochs of observation emanating preferentially from over the polar rather than over the equatorial regions. The sky-projected mean position of these peaks lies within about 35% of the distance from the center to the surface of the primary. Another inference is that about two-thirds of the peaks originate at altitudes below about 25% of the radius of the primary.

Paper VII (Bietenholz et al. 2011) focuses on the images of the guide star for all of our observing sessions. The image for IM Peg for each session was made via the phase-referenced mapping method. Included in the paper is a short movie that shows the temporal behavior of the radio brightness distribution of the guide star over our ~ 8.5 years of VLBI observations. Unfortunately, the sparse and uneven spacing of the epochs of observation make the presentation somewhat “choppy.” But two main points are clear: (1) the time-variable sky positions of the radio source, relative to the putative position of the primary component of the guide-star binary system, and (2) the time-variable brightness distribution of the source. Each of these appears to change chaotically with time, albeit within the “reasonable” ranges also discussed in Papers V and VI. In an attempt to explain some of the aspects of the brightness-distribution changes, the paper proposes a speculative model based on an assumed dipolar magnetic field of the primary. This model finds some support in the comparison of its predictions with the observed positions and shapes of IM Peg’s radio brightness distribution at our observing epochs.

7. Double-Blind Experiments

It is best that an experimenter not know the “right” result in advance. Why? To avoid possible bias, whether conscious or unconscious. This possibility of bias is probably most important to suppress in experimental tests of GR. Present experiments are far from probing any quantum limit of GR and the a priori expectation among physicists is extremely high that far from this or the so-called strong-field limit, this theory will be valid for currently accessible accuracy levels. In a typical experiment, those involved carefully examine all its aspects to assess the likely level of systematic errors as well as the contribution of random errors. Although similar in principle, a GR experiment may be different in practice: In essence, if experimenters obtain the “wrong” answer, they re-examine the experiment in excruciating detail, looking for a possible error; when they obtain the “right” answer, they publish. To eliminate this type of bias, a double-blind experiment would be ideal. Although this approach is not often feasible in a physics experiment, the *GP-B* mission, in principle, offered this opportunity. The measurement of the changes in direction of the gyroscopes were made with respect to the guide star, whose proper motion was indeed already known but with an uncertainty about tenfold higher than the expected uncertainty of the measurements of the gyro precessions.

One idea was to have the *GP-B* group at Stanford determine, without our knowledge, the apparent proper motion of the guide star relative to the *GP-B* gyros on the assumption that GR was correct, thus approximating the proper motion of the guide star as we measured it, i.e., with

respect to the distant universe. Our group, without the Stanford group’s knowledge or involvement, would determine the proper motion of the guide star with respect to a nearly inertial frame defined by compact extragalactic radio sources representing the distant universe. After both groups had completed their analyses, they would get together. Our group’s result would be subtracted from Stanford’s (or vice versa) and the result checked to see whether it is zero to within the estimated errors—confirmation of GR—or significantly different from zero—incompatible with GR. This comparison would take place in the presence of knowledgeable neutral observers and possibly representatives of the media – an unusual scientific gathering! Of course, in the end, the double blindness of the experiment would depend on the integrity of the members of each group to keep their results totally to themselves until the comparison event.

Alas this plan was not to be carried out. There were two problems:

1. The accuracy of the pre-mission value of the guide star’s proper motion (ESA 1997) was improved about twofold and made public (van Leeuwen 2008); and
2. The accuracy of the *GP-B* measurements of the guide star’s motion in the gyro frame decreased about twentyfold compared with the pre-mission expectations. Thus, the uncertainty published for the guide star’s proper motion ($\sigma \approx 0.3 \text{ mas yr}^{-1}$ in each coordinate; van Leeuwen 2008) was substantially under that of the *GP-B* determination of the motion ($\sigma \approx 7 \text{ mas yr}^{-1}$ in right ascension and 18 mas yr^{-1} in declination; Everitt et al. 2011). Within these larger-than-expected uncertainties, the three proper-motion estimates agreed.

Our VLBI determination (Paper V) of IM Peg’s proper motion thus becomes useful primarily as an accurate check, with $\sigma \leq 0.10 \text{ mas yr}^{-1}$ in each coordinate.

8. Conclusion

Our VLBI observations represent the most comprehensive set of radio images ever obtained on a star. We find that:

1. The proper motion of IM Peg on the plane of the sky (i.e., in local Cartesian coordinates) is $-20.83 \pm 0.09 \text{ mas yr}^{-1}$ and $-27.27 \pm 0.09 \text{ mas yr}^{-1}$ in right ascension and declination, respectively;
2. The parallax and distance to IM Peg are, respectively, $10.37 \pm 0.07 \text{ mas}$ and $96.43 \pm 0.69 \text{ pc}$;
3. The centers of the maps obtained from our 35 sessions of VLBI observations moved erratically from session to session with respect to our estimate of the sky position of the primary component of the binary guide star;

4. For one session there was a remarkable correlation (Lebach et al. 1999) between rapid changes in total radio brightness of IM Peg and corresponding changes in sky position of the radio source, at about the quarter-hour limits of our useful time resolution. Other sessions showed similar, but not as definite, relations between changes in radio-source flux density and changes in its sky position. These features of this radio star cry out for more quantitative theoretical understanding than is provided by our mostly qualitative speculations in Lebach et al. (1999) and in Paper VII; and
5. The 1σ uncertainty in our determination of the proper motion of IM Peg is about 30% less than the accuracy goal of 0.15 mas yr^{-1} set by the GP-B project.

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